

A Human Factors Approach to Range Scheduling for Satellite Control

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ABSTRACT

Range scheduling for satellite control presents a classical problem: supervisory control of a large-scale dynamic system, with unwieldy amounts of interrelated data used as inputs to the decision process. Increased automation of the task, with the appropriate human-computer interface, is highly desirable. This paper describes the development and user evaluation of a semi-automated network range scheduling system incorporating a synergistic human-computer interface consisting of a large screen color display, voice input/output, a "sonic pen" pointing device, a touchscreen color CRT, and a standard keyboard. From a human factors standpoint, this development represents the first major improvement in almost 30 years to the satellite control network scheduling task.

1. INTRODUCTION

To maintain today's large number of satellites in their various orbits, it is necessary to schedule regular contacts with them using a global network of satellite tracking and control facilities. During the early days of the military space program, the complexity of the satellite control scheduling task was low enough that a daily schedule of satellite contacts could be easily represented with a paper chart. Data representing satellite/ground station visibility, resource allocation, and conflict resolution could be assimilated by scheduling personnel in an acceptable manner using this method.

However, continued growth in number, size, and complexity of both ground and space assets, combined with the increased dependence on these resources for national defense, has made it necessary to search for a more effective methodology for network scheduling. The Air Force Satellite Control Network (AFSCN) is a large-scale system which provides the essential command, control, and communications (C³) support to orbital space vehicles using internettted facilities located across the globe. The task of scheduling these network assets effectively is a challenging problem of supervisory control [1]. On any given day, interrelated information depicting nearly 1600 entries of satellite visibility and scheduled network support must be interpreted and used to make decisions that can be critical to the survival of valuable orbital assets [2]. Given an environment which must account for unexpected equipment outages, satellite anomalies, and changing mission priorities, the scheduling task can exceed acceptable workload levels.

While recent attempts to fully automate this task have

been less than satisfactory, it is within the state of the art to implement a partially automated system with human-in-the-loop decision making. This system must effectively convey large amounts of interrelated data to the scheduler and allow the scheduler to manipulate this data and to input selected commands at will. These requirements indicate that an optimized human-computer interface (HCI) is a critical design aspect of such a system [3].

This paper describes the development and user evaluation of a semi-automated network scheduling system incorporating a synergistic HCI consisting of a large screen color display, voice input/output, a "sonic pen" pointing device, a touchscreen color CRT, and a standard keyboard.

2. THE PROBLEM DOMAIN

Before we can examine the HCI design, we must first understand the activities involved in satellite control network scheduling. While there are many similarities between scheduling support for civilian satellites [4,5] and for military satellites [2,3], we concentrate here on the latter. Military satellites include many low earth orbiters, which, because of their brief "windows" of satellite/ground station visibility, make the scheduling task more difficult than with the predominantly geosynchronous civilian satellites.

Traditionally, scheduling was performed using a paper acquisition chart. The horizontal axis of the chart represents time, and the vertical axis shows the resources for each ground station of the AFSCN, commonly referred to as Remote Tracking Stations (RTS). A single paper chart encompassing a 24-hour period measures 36" vertically by 144" horizontally, with extremely high information density. Three types of schedules are maintained: a seven day forecast, a 24-hour schedule, and a real-time schedule. The basic scheduling activities are listed below, and a flowchart of a typical real-time response to an RTS outage is shown in Figure 1.

- Receive new or modified request for satellite support.
- Validate acquisition data and satellite/RTS visibility.
 - Compare new data with most recent data from scheduling database.
 - Slide supports along time axis of chart to accommodate changes.
- Assign or modify satellite support(s).
 - Visually scan chart for resource availability.
 - Enter support(s) on chart.

Prepare schedule.
 Identify time/resource conflicts.
 Scan chart for alternate support possibilities.
 Propose alternative solution to Mission Control Center.
 Reassign supports as approved and notify RTS.
 Enter new support on chart.
 Update scheduling database to reflect latest chart.

It is important to note how the scheduling chart is central to these activities. It contains a large amount of information relating to the various satellites, RTS resources, and visibilities for the entire world-wide AFSCN by using twenty-nine distinct variations of symbology and annotation style [2]. This graphical representation enables the scheduler to view the "big picture" at a glance, make the necessary RTS assignments, identify conflicts, and resolve them

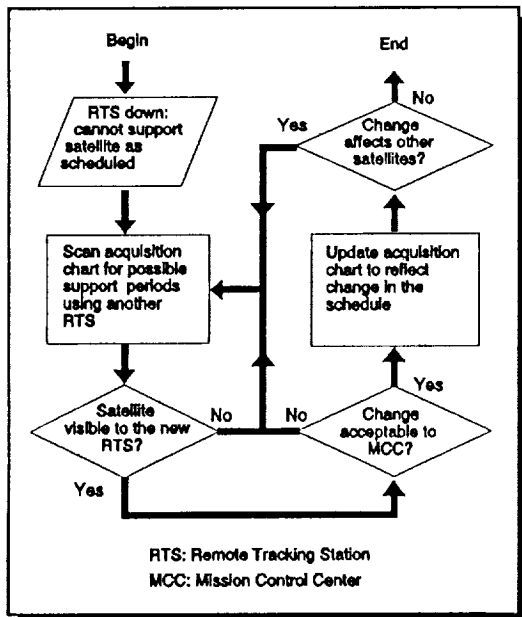


Figure 1. Typical task flow for an unexpected RTS outage [3].

quickly. This is especially critical during real-time scheduling, which is driven by random events (satellite anomalies, RTS equipment outages, changing mission priorities, etc.). The main drawback of the paper chart is that it is a totally manual process, which has become increasingly unmanageable due to the trends identified in Section 1 above. Greater automation of the scheduling task is highly desirable; benefits would include a more acceptable scheduler workload, reduced chance for human error, and greater responsiveness to highly dynamic national security priorities. However, any acceptable design must incorporate into the HCI those positive aspects of the paper acquisition chart outlined above.

3. ASTRO: A NEW APPROACH

The importance of a well designed HCI has been documented extensively in the literature [6-11]. Recently,

significant progress has been made [2-5] in investigating optimal HCIs for various satellite control tasks. The GT-MSOCC simulator at Georgia Tech, for example, has addressed many aspects of NASA satellite operations. However, the Air Force had a pressing need to address the problem of network scheduling for satellite control in an operational military environment.

Initial designs to solve this problem proposed an HCI using standard CRTs, which were limited to displaying only a small subset of the information contained in the paper chart. It was thought that the use of panning, scrolling, zooming, and windowing techniques could overcome this limitation and provide an equivalent capability. However, experienced scheduling personnel evaluated this approach as unacceptable; their stated requirement was to view all the information that the paper chart provided with at least 12 hours of data on a single display. It has been shown [3] that human factors design considerations support this position in that the necessity of accessing multiple sequential displays forces excessive reliance on the short-term memory of the schedulers, resulting in increased error rates. In particular, the error rate increases proportionally with the number of screen accesses required, and with the time required to perform those accesses. By taxing short-term memory, the perceived workload and level of stress experienced by schedulers would actually increase compared to using the paper chart, and scheduling productivity would go down. A new design approach for the HCI was required, and the Automated Scheduling Tools for Range Operations (ASTRO) project was started in October 1987. ("Range" here denotes the networked RTSs of the AFSCN.)

In order to satisfy the core requirement of providing 12 hours of scheduling data on one display, a high resolution, large screen color display is required. Analysis indicates that an approximate displayable resolution of 3K vertical points and 4K horizontal points is necessary [2]. (Note that manufacturer specifications typically cite only addressable resolution, which is generally two to four times greater than displayable resolution.) For comfortable viewing of 7x9 format characters, the screen size should be roughly 25" vertically by 42" horizontally [2]. A 12-hour section of the paper chart was photo-reduced to validate these derived estimates. Further requirements include at least 16 colors, ability to mix graphic symbols with characters, imperceptible flicker, low noise level, standard computer interface, standard power and cooling needs, high MTBF, and low MTTR. While these requirements push state-of-the-art display technology, the best match was found to be a continuous projection, laser addressed system using smectic liquid-crystal light valves, produced by Greyhawk Systems [12]. It displays 4096 colors with 2.2K V by 3.4K H displayable resolution on a 22" by 34" screen with excellent clarity and detail, has a contrast ratio of 16:1, a very wide viewing angle, and can be used in normal ambient lighting. A 12 hour acquisition chart representation was found to be quite readable on the Greyhawk display. While the Greyhawk meets the primary display requirement, an effective HCI is a coordinated ensemble; thus we now turn our

attention to data entry and manipulation.

Observations have shown that even skilled typists can update a paper chart faster than they can update a computer display using a standard keyboard; alternatives are required [2]. Because the Greyhawk does not produce sync pulses, a light pen is not feasible. A mouse, while usable, would take away too much valuable horizontal workspace. An effective solution for a pointing device was found to be the GP-8 Sonic Pen from Science Accessories, which utilizes audio detectors mounted on two orthogonal edges of the Greyhawk display. The GP-8 controller computes the pen location based on the time-of-arrival of a sonic pulse emitted by the pen when pressed to the screen. The pen is used to both identify specific points on the large screen display, and to select items from standardized pop-up menus via appropriate display interface software [13-15]. While the sonic pen can be used for many tasks, a keyboard would still be required for some alphanumeric entry. Voice-augmented keyboards have been shown to alleviate this potential bottleneck [16]; thus, a Verbex 5060 voice I/O system from Voice Industries was incorporated into the ASTRO HCI design. Using a headset and an intelligent controller, this device supports a continuous speech grammar of up to 600 words; ASTRO required only a 50 word grammar. Initial training of the V-5060 for each speaker required one hour, but resulted in reliable recognition rates of better than 95% for all speakers, and a maximum response time of 0.5 seconds [2]. In addition to the Greyhawk display, a 19" color (VGA) CRT with an Elo-graphics touchscreen overlay was integrated into the HCI to allow operator access to secondary screens and menus, and as a system monitor for the Compaq 386/25 computer that runs the ASTRO software. The sonic pen was also capable of selecting items on the touchscreen CRT, allowing the operator to use the same pointing device for both displays.

The ASTRO HCI is a synergistic combination of a large screen display, a sonic pen, voice I/O, an ancillary touchscreen CRT display, and a standard keyboard, which allows effective manipulation of the schedule data, minimizes the required keyboard entry, and greatly reduces the time required to perform scheduling tasks. See Figure 2 below, and Photo 1 and 2 following the text.

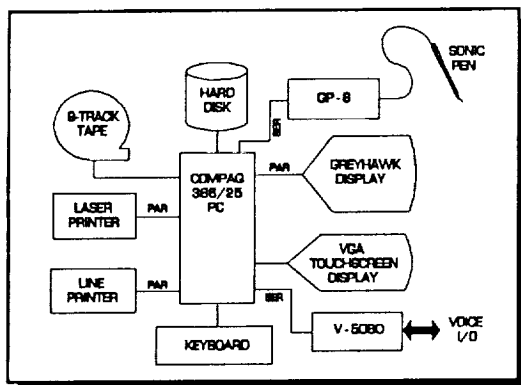


Figure 2. Block diagram of ASTRO workstation.

While ASTRO certainly meets the design goal of improving the methodology for satellite control network scheduling, it also has potential to provide a multi-node, simultaneous scheduling capability never before possible. By connecting multiple units via LAN, WAN, or standard telephone lines, users at different locations could manipulate a shared schedule database, thus improving coordination and wartime survivability.

4. USER EVALUATION

The most effective HCIs result from the user being involved early in the design phase. ASTRO was managed as a prototype project, where instead of copious reports, documentation, and formal design reviews, system demonstrations were given to representative users at frequent intervals during the development. This allowed user feedback to guide the design process. During the initial development period, 40 system demos were given to 320 people with space operations and scheduling backgrounds to solicit their suggestions. Following this, ASTRO prototypes were installed at the two major control nodes of the AFSCN: Falcon Air Force Base (FAFB) in Colorado Springs, CO, and Onizuka Air Force Base (OAFB) in Sunnyvale, CA. An extensive functional evaluation study was conducted from August 7, 1989 to December 8, 1989, and resulted in an extremely favorable final report [17]. Areas and subareas evaluated on a scale of 1 (worst) to 5 (best) were: Functional Requirements (Information Display, Operator Capabilities, Scheduling Functions), Performance Requirements (Display, Functional), Human Factors (Workspace, Displays, Pointing Device, Keyboard, and Voice Input), plus an overall system rating. We concentrate here on a preliminary analysis of the Human Factors area, which rated the HCI. While further statistical analyses will be conducted, Figure 3 depicts the group average ratings given in each subarea, with the overall system rating also shown for comparison.

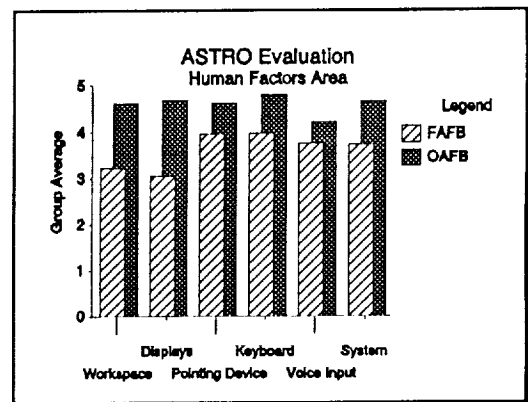


Figure 3. Average HCI evaluation ratings [17].

Note that while the evaluations are very good, the OAFB schedulers consistently rated the ASTRO HCI and the overall system higher than those at FAFB. We feel that this may be due to the fact that while the satellite

control and scheduling tasks have been performed at OAFB for 30 years with only recent help from modern tools, FAFB is a new facility with the latest equipment, possibly leading to less appreciation for the advances represented by ASTRO. Further, latent shipping damage to the unit at FAFB resulted in some early reliability problems, which may have biased some of the evaluations. Despite these caveats, ASTRO received enthusiastic response from the schedulers at both nodes.

Following publication of the evaluation final report [17], ASTRO was given two weeks of full operational testing, and performed very well. As a result, Air Force Space Command has submitted formal documents requesting installation of ASTRO at both nodes to support operational scheduling of the AFSCN.

5. CONCLUSIONS

It has been shown that the network scheduling task for satellite control has grown in complexity until the traditional method of using a paper chart representation is insufficient. The desire of the human schedulers to retain the graphical aspects of the paper chart for ASTRO was shown to have a logical basis in human cognitive abilities. The engineering challenge of representing such a data intensive display in a usable format, while allowing efficient supervisory control of the scheduling task, was met by designing an optimized HCI for ASTRO. This interface consists of a large screen color display, a voice input/output subsystem, a sonic pen pointing device which can be used both with the large screen display and the ancillary touchscreen CRT display, and a standard keyboard. Extensive evaluation of the ASTRO system indicated a high level of user satisfaction with ASTRO overall, and its HCI in particular. As a result of this evaluation, Air Force Space Command has recommended that ASTRO be used for full-time scheduling of operational military satellites. Further research is needed to investigate integration of appropriate artificial intelligence technology into the ASTRO design, particularly in the area of automated conflict resolution, and to investigate implementation of networked ASTRO units.

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REFERENCES

- [1] T. B. Sheridan, "Toward a general model of supervisory control," in *Monitoring Behavior and Supervisory Control*, eds. T. B. Sheridan and G. Johanssen, Plenum Press, New York, 1976.
- [2] J. L. List et al, "Range Scheduling Via Large-Screen Displays, Phase I-IV," Unisys Corp., Sunnyvale, CA, 1989.
- [3] D. E. Egbert et al, "Analysis of Man-Machine Interfaces for the Network Scheduling System," (AFSCF-TR-86-101), Ford Aerospace and Communications Corp., Sunnyvale, CA, 1986.
- [4] C. M. Mitchell, "GT-MSOCC: A domain for research on human-computer interaction and supervisory control systems," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. SMC-17, no. 4, pp. 553-572, 1987.
- [5] C. M. Mitchell and T. Govindaraj, "A tutor for satellite operators," *Proc. 1989 IEEE Int. Conference on Systems, Man, and Cybernetics* (Cambridge, MA), pp. 766-771, Nov. 1989.
- [6] E. J. McCormick and M. S. Sanders, *Human Factors in Engineering and Design*, 5th ed., McGraw-Hill, New York, 1982.
- [7] S. K. Card, T. P. Moran, and A. Newell, *The Psychology of Human-Computer Interaction*, Lawrence Earlbaum Associates, Hillsdale, NJ, 1983.
- [8] E. Grandjean and E. Vigliani, eds., *Ergonomic Aspects of Visual Display Terminals*, Taylor and Francis, London, 1980.
- [9] National Aeronautics and Space Administration, *Bioastronautics Data Book* (NASA SP-3006), U.S. Government Printing Office, Washington, D.C., 1973.
- [10] Department of Defense, "Human Engineering Design Criteria for Military Systems, Equipment, and Facilities," (MIL-STD-1472D), U.S. Government Printing Office, Washington, D.C., 1989.
- [11] R. A. Olsen, ed., "Handbook for Design and Use of Visual Display Terminals," (Tech. Rep. LMSC 62-91), Lockheed Missiles and Space Company, Sunnyvale, CA, 1982.
- [12] F. J. Kahn et al, "A paperless plotter display system using a laser smectic liquid-crystal light valve," *Society for Information Display International Symposium Digest*, paper 14.1, 1987.

- [13] S. W. Draper and D. A. Norman, "Software engineering for user interfaces," *IEEE Trans. Software Engineering*, vol. SE-11, pp. 252-258, 1985.
- [14] S. L. Smith, "User-System Interface Design for Computer-Based Information Systems," (Tech. Rep. MTR-8464), MITRE Corp., Bedford, MA, 1982.
- [15] S. L. Smith et al, "Guidelines for Designing User Interface Software," (ESD-TR-86-278), MITRE Corp., Bedford, MA, 1986.
- [16] C. M. Mitchell and M. G. Foren, "Multimodal user input to supervisory control systems: voice-augmented keyboards," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. SMC-17, no. 4, pp. 594-607, 1987.
- [17] F. S. Watson et al, "ASTRO Evaluation Final Report," Air Force Space Command (Det 9, 2STG/TA), Falcon AFB, CO, 1990.

PHOTOS

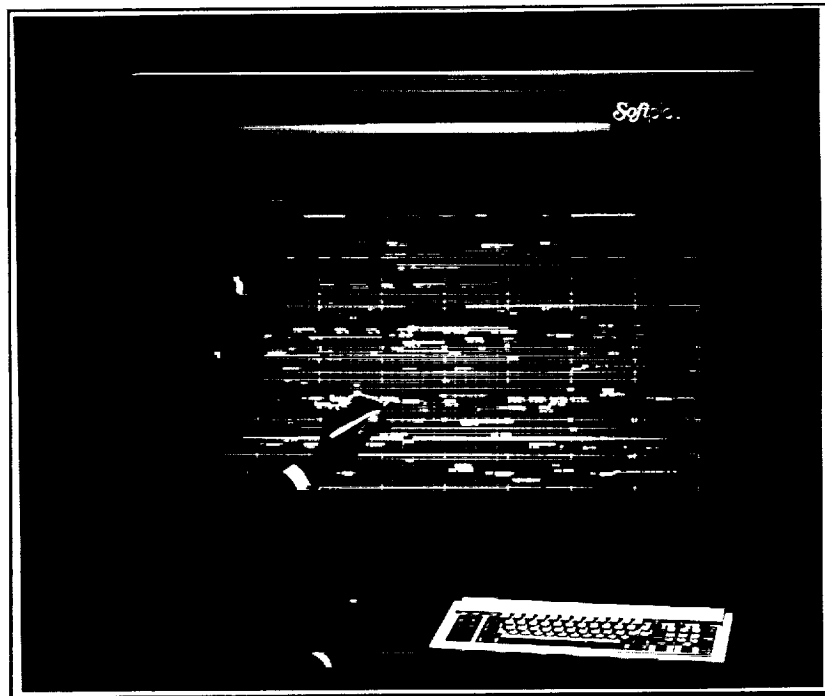


Photo 1. Overall view of the ASTRO workstation.

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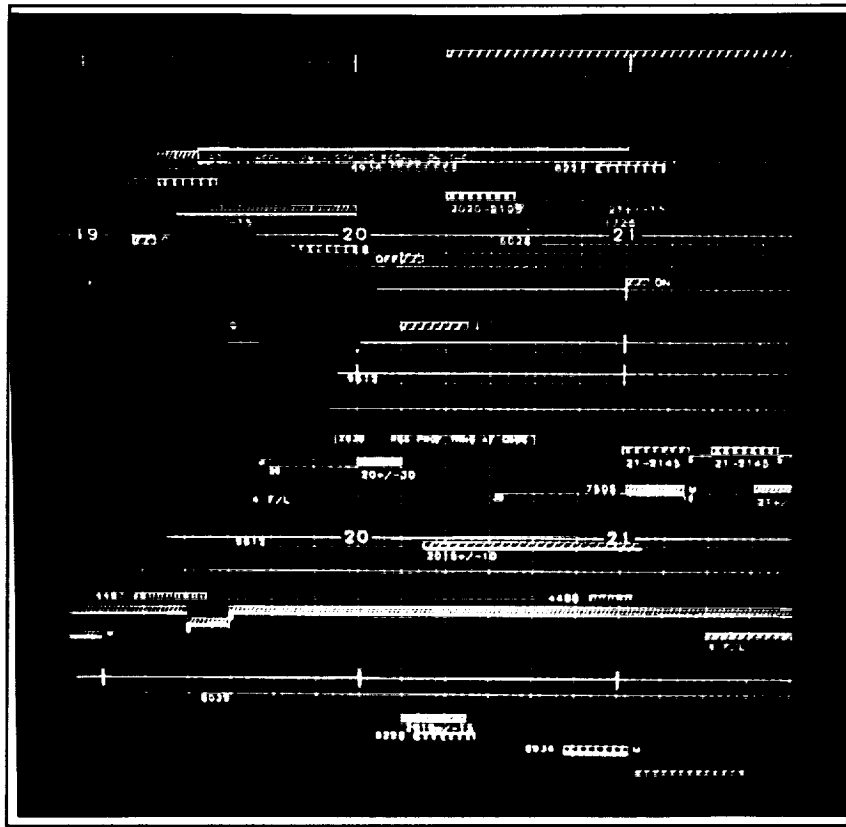


Photo 2. Closeup of the ASTRO main display screen.

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